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Sensitivity Analysis of Transmission Assets: Special Case Transformers Aging

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Abstract— **The paper describes initial research undertaken, exploring the impact of demand and other environmental factors on the power transmission network. How these factors lead to a determined probability of failure is currently determined through a set of complex equations. Demand, or loading, is expected to be the principal factor on the expected life of transmission assets such as transformers. The long-term aim of the research is to understand the likely impact of electrification of vehicles, the associated increased demand on the network, leading to the prospect of a deterioration of the network assets. This initial research suggests that transformer ageing is highly sensitive not only to the average and maximum demand in the network but also to other environment factors. Recommendations from this research will help power transmission companies to more effectively manage their assets through a more robust understanding of the ageing of assets as a consequence of Governmental policy shifts on electric vehicle uptake.**

Keywords — asset end of life, transformer ageing, sensitivity analysis.

I. Introduction

Any energy transmission infrastructure consists of assets, each with a planned life expectancy. These assets need to be monitored for likelihood of failure, since any resulting network outage carries significant consequences to the transmission network owner and the users. In the UK, electricity supply industry is operated by major private sector companies but is regulated by the Office of Gas and Electricity Markets (Ofgem) whose principal role is to protect consumers and to deliver a greener and fairer energy system [1]. The energy companies periodically identify a capital replacement programme, designed to maintain the reliability of the network. This programme requires agreement and acceptance by Ofgem.

Electricity generators in the UK are owned by privatised companies that produce and supply electricity to the national electricity grid. Energy transmission networks are also owned by privatised regional transmission companies, that are responsible to transmit electricity across national grid at high voltage and low loss, while the whole system is operated by a single Electricity System Operator (ESO). Its role is to ensure the total system is stable and secure to operate. Currently National Grid Electricity System Operator (NGESO) is acting as ESO in the UK [2]. There are three transmission operators in the UK at this moment, namely National Grid Electricity Transmission plc (NGET) for England and Wales, Scottish Power Transmission Limited for southern Scotland and Scottish Hydro Electric Transmission plc for northern Scotland and Scottish islands groups [3].

Load related activities include adjusting the network to cope up with the changing demand, adding or disconnecting generators to or from the network, to conform with the service standards set by Ofgem [4]. Non-load related activities are the monitoring, inspection, refurbishment or replacement of the assets like transformers, substations, tower, overhead lines, cables, etc to ensure the reliability set by the regulator [4]. These assets are called non-load assets.

Lead assets are the main assets that are required to transmit electrical energy from one point to another in the electricity transmission network over 132 kV, such as transformers, reactors, circuit breakers, overhead lines, underground cables, etc [5]. Non-lead assets are other assets of the electrical power transmission system including the lead assets types below 132 kV [5].

One lead asset identified is the transformer whose life expectancy depends on a number of factors, but most significantly on the load delivered. The more load delivered, the more current passing through the transformer, leading heating of the winding. As a consequence, insulation can be degraded mainly due to chemical reaction between insulation and coolant oil. Authors of [6] has examined the impact of high level of electric vehicles (EV) charging loads on aging of transformer. In this paper authors are considering all the relevant variables such as distance to coast, altitude, corrosion zone, environmental impacts, demand, age, humidity, oil breakdown voltage, oil acidity, main tank surface condition, oil leaks, radiator fins, conservator, cable and box, dissolved gases. Therefore, this research is more comprehensive rather than evaluating the impact of a specific variable.

Most transformers deteriorate through time with insulation aging faster than other transformer components. Insulation age during operation of transformer. Considering the cost of replacement of insulation and the value of the transformer, it is often simpler to replace the entire transformer, making insulation a key determinant in the lifetime of a transformer.

Authors of [7] has provided details about transformer insulation types and insulation ageing mechanisms. Thermal, electrical and chemical stresses on the insulation system causes irreversible change and degrade it. The main causes of thermal degradation are oxidation and hydrolysis [8], [9]. Oxygen, water and acids present in oil reacts with the cellulose-based insulation system, further affected by high temperatures [8]. These chemical reactions are accelerated by a factor of two for every 6-8 degrees of increased temperature [10], [11]. Transformers generally heat up to 40-80 degree Celsius during normal operation. At this temperature range, insulation systems age slow and steadily. Yet temperature increases with increased loading and when temperature reaches 110 degrees Celsius and beyond, transformer insulation can degrade rapidly. Thermally upgraded paper insulation can sustain this high temperature.

There are two types of insulation: major insulation and minor insulation. Major insulations are between core and Low Voltage (LV) winding, LV and High Voltage (HV) winding, top and bottom of winding and yoke, HV winding and tank, and bushings. Minor insulations are between conductors, turns, layers, laminations, joints and connections. Insulation material consists of paper, pressboard and transformer board. All of these are formed from the cellulose of plants. The main problem with this cellulose insulation is these are very hygroscopic.

Hot-spot temperature is the temperature of the hottest spot in a transformer. Usually, it is found on the winding top. Insulation ageing depends highly on temperature. As the hot-spot temperature is the highest in a transformer, it is here insulation ages most quickly. For this reason, hot-spot temperature is considered an important factor in transformer ageing.

Dissolved Gas Analysis is tool to identify condition and incipient problems in a transformer [12]. Sample oil is taken from the transformer and then gases in the oil are extracted in laboratory. The concentrations of nine gases namely Hydrogen H_2, Methane CH_4, Ethane C_2H_6, Ethylene C_2H_4, Acetylene C_2H_2, Carbon Monoxide CO, Carbon Dioxide CO_2, Oxygen O_2, Nitrogen N_2 are determined. Then using Duval's triangle, depending on concentration of Methane, Ethylene and Acetylene, six types of fault can be identified [13]. These are high energy arcing, low energy arcing, corona discharge, hot spot temperature $T < 200°C$, $200 < T < 400°C$, $T > 400°C$. On the other hand, transformer furfuraldehyde (FFA) analysis is a measure the degradation of transformer insulation and identify its remaining life. Furan derivatives concentration in transformer oil is directly related to its insulations DP [7]. From this, probability of failure can be determined, depending on the intensity of fault.

Probability of failure is the measurement of probability of an asset to fail [14]. Fail means it will not do what it is designed to do fully or partially and it may contribute to the failure of other assets that are directly or indirectly connected to it.

Transformers, reactors, circuit breakers, underground cables, overhead lines, towers, conductors and fittings are the principal lead assets that have potential risks of failure. Tap-changers and bushings are included in the transmission transformer system. Overhead lines include towers, conductors and fittings. Tower steelwork contains tower legs, step bolts, bracing, crossarms, peak and steelwork. Fittings include insulators, arcing horns or corona rings, jumpers, vibration dampers, U-Bolts or tower attachments, shackles or links, suspension clamps, tension clamps and conductors at clamps. However, the transformer remains the most expensive asset.

The transmission networks and their assets are expected to undergo significant change, particularly in terms of how energy will flow through the network. This is expect because of (a) the increased use of renewable energy sources that have a wide geographic distribution and (b) the decarbonisation at the household level through the adoption of electric vehicles and air source low grade heat pumps.

This ongoing research focuses on the impact of electric vehicles, on the load demand and the likely impact on life expectancies of transformers in particular. This should ultimately inform future investment plans needed to replace transformers and adapt the network.

II. The Impact of Electric Vehicle Charging on Network Demand

There will be increases in peak demand due to extra load during Electric Vehicle (EV) charging times and in overall demand. Also, there can be a decrease in voltage also known as voltage sag at the distribution feeders, which is a power quality issue. The excess load due to electric vehicle charging will draw extra current, that will flow through transformers, generating extra heat in the windings leading to insulation life loss. Power system operators usually dispatch economic generators, first in terms of fuel cost and environmental impact (carbon emission) and if required, the more expensive ones. Due to increased loading, there can also be an increased peak demand. Therefore, there is a possibility that less efficient generators will be dispatched during peak demand. That will not only affect customers financially but also affect the environment with any associated carbon emissions.

Therefore, proper estimation of increased demand due to electric vehicles needs to be appropriately determined. To do that, penetration levels of EV on the electrical network needs to be estimated. As of Oct 2020, there are a total 40 million vehicles in the UK, consisting of 32.8 million cars, 4.3 million light goods vehicles, 508,000 heavy goods vehicles, 144,400 buses and coaches [15]. In terms of EVs there are 164,100 pure-electric cars, 373,600 Plug in Electric Vehicles and 10,300 Plug in Vans [16].

While in the UK EV penetration is only 0.5%, Figure 1 shows that the global EV market share is expected to be ~35% by 2030 and its adaptation is expected to continue to increase each year [17]. In this research authors will simulate market penetration level from 0% to 50%. Moreover, in the UK there is an increasing adoption of electric trains, with HS2 expected to be operational in next 10 years, running on 25 kV 50 Hz AC overhead line equipment (OHLE) [18].

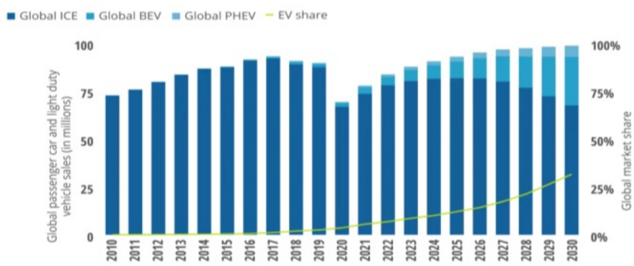
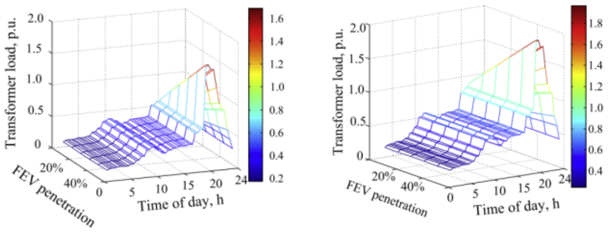


Fig 1. Outlook for annual global passenger-car and light-duty vehicle sales, to 2030 [17].

In the UK, the average domestic load is 8 kWh per day [19]. After well adaptation of EVs it is expected to potentially double. Impact of high penetration level of EVs are discussed in [6]. Figure 2 shows the transformer overloading due to increased charging of EVs. Therefore, distribution transformers would face unprecedented stress. Either the capacity of transformers, transmission lines would need to be increased or load levelling mechanisms would be required to be implemented. Load levelling may include shifting some portion of load to the off-peak hours. It will reduce the peak demand and increase the off-peak demand and eventually flatten the demand profile at the distribution end. It can be done by increasing the electricity price at the peak hours and reducing price at off-peak hours.



(a) summer weekday (b) winter weekday

Fig 2. Power load of domestic transformer and its aging. Red means 1.8 times aging comparing with full load aging [6].

Section III contains simulation results for different demand levels to assess the impact of EV charging on transformer aging.

III. Simulation and Results

The researchers were provided with an extract from a database of lead asset data provided by one of the major transmission companies and used the broad equations set out in [7]. In the simulation about to be described, a 90 MW transformer is selected from the database. Each transformer has its distinct ID, that reflects its manufacturer, location, ratings and any other information. Its operating voltage is 132 kV and placed in a completely enclosed situation. Its average load is 12 MW and maximum load is 22 MW. The end of life variable of a transformer, denoted as $TxEoL_{Y0}$ is simulated by changing values of different variables and using equation (1).

$$TxEoL_{y0} = \min\left(Max\left(EoL_{DGA}, EoL_{FFA}, EoL_{max,min}\right), EoL_{y0,\max}\right) \quad (1)$$

End of life (EoL) is a continuous variable in the scale of 0.5 to 15. Its value from 0.5 to 2.5 means the transformer's condition is new or as new. Values from 2.5 to 4.5 represents a good or serviceable condition. 4.5 to 6.0 indicates there is an onset of significant deterioration. 6 to 8 means there is significant deterioration and finally more than 8 means there is serious deterioration and threatened failure [20]. EoL_{Y0} is the current end of life. $TxEoL_{y0}$ is the transformer current end of life.

A. Distance to coast

There is an inverse correlation between distance to coast and $TxEoL_{Y0}$ as shown in Figure 3.

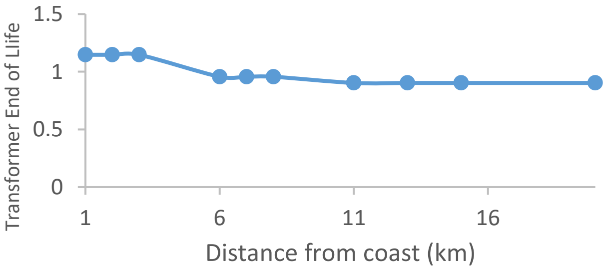


Fig 3. Effect of distance to coast on $TxEoL_{Y0}$.

Transformers that are situated far away from the coast are subject to less humidity and salty vapours. Therefore, those exhibit lower $TxEoL_{Y0}$. These play a significant role on the life span of the transformers.

B. Altitude

There is a positive co-relation between altitude and $TxEoL_{Y0}$. Altitude did not have effect on the $TxEoL_{Y0}$ for this transformer due to its low distance to coast resulting in high value of the distance to coast factor. Factor values corresponding to many variables are obtained from [21] and can be used to interpret the variables into a standardized form and combine them into a single value to understand the overall effect of altitude.

C. Corrosion zone

There is a positive correlation between corrosion zone and $TxEoL_{Y0}$. As anticipated, if the transformer is in high corrosion zone, then it will deteriorate faster. Corrosion zone did not affect $TxEoL_{Y0}$ of the selected transformer due to high value of distance to coast factor.

D. Environmental impacts

There is a direct correlation between environment and $TxEoL_{Y0}$. Transformer environment is rated from 1 to 5. Where 1 is the normal environment and 5 is severe environment such as dust and pollution etc. There can be more dust in the air in industrialised areas, or example. These dusts can accumulate around the insulators, reduce their insulating capacity and can result in tracking, increasing the risk of failure of the transformer. A high environmental rating will deteriorate the transformer faster. Figure 4 shows this relationship. As shown, there is a 21% more degradation in $TxEoL_{Y0}$ depending on environmental rating from 1 to 5. Environment factor ranges from 1 to 1.2 for environment rating 1 to 5. This factor value is standardized to compare environmental effect to other variables such as altitude, corrosion zone etc.

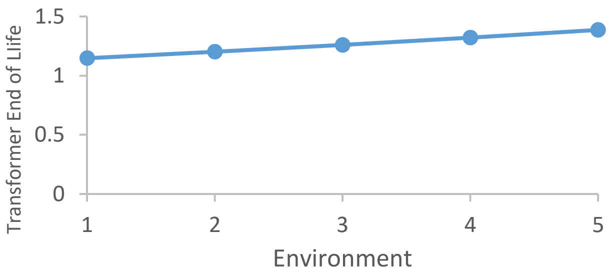


Fig 4. Effect of environment on $TxEoL_{Y0}$.

E. Maximum demand impacts

There is a positive correlation between maximum demand and $TxEoL_{Y0}$ as shown in Figure 5. As describe earlier, transformers heat up with greater demands, leading to faster deterioration of the transformer insulation.

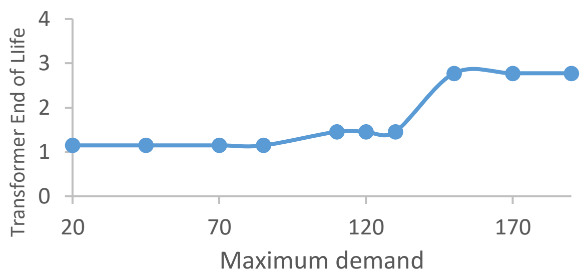


Fig 5. Effect of maximum demand on $TxEoL_{Y0}$.

Effect of maximum demand seems to be particularly significant when overloaded at over 130% as shown in Figure 5. Also, if the transformer is under-utilized, its life is prolonged. The following factors are affected by demand: the duty factor F_{DY}, the expected life, L_E and the initial ageing rate B_i. These determine the initial end of life, EoL_1 and finally, the intermediate end of life, EoL_2. Duty factor is the maximum of the maximum demand factor and average demand factor. Maximum demand factor and average demand factor are converted variables of maximum demand and average demand in percentage of transformer rating. From [21] maximum demand factor ranges from 0.8 to 1.5 for 0 to 100% and 130% to 200% maximum demand. On the other hand average demand factor is also a converted variable that ranges from 0.8 to 1.5 for 0 to 40% and 100% to 200% average demand. The maximum demand factor and average demand factor allow comparisons of different values of average demand and maximum demand, combining into a single variable that can be used in the calculation of transformer end of life. Expected life, L_E is the expected lifespan of the transformer for the given location, situation and environment and duty factor. For the selected transformer it is 46.64 years. Initial aging rate, B_i is the initial rate of aging of the transformer so that the transformer will reach EoL 5.5 from its new condition (EoL 0.5). Initial end of life, EoL_1 is the end of life of the asset considering its age, average life, duty, location, situation and environment. Test results such as visual condition, oil condition and defect history and operating restrictions are considered to decide the intermediate end of life, EoL_2 . After that, DGA and FFA test results are considered and to calculate the current end of life of the asset, EoL_{Y0}. It is denoted as $TxEoL_{Y0}$ for a transformer.

F. Average load impacts

Similar to maximum load impacts, there is a positive correlation between average demand and $TxEoL_{Y0}$ as shown in Figure 6. Transformers heat up more for higher average demand, leading to faster deterioration of the transformer insulation.

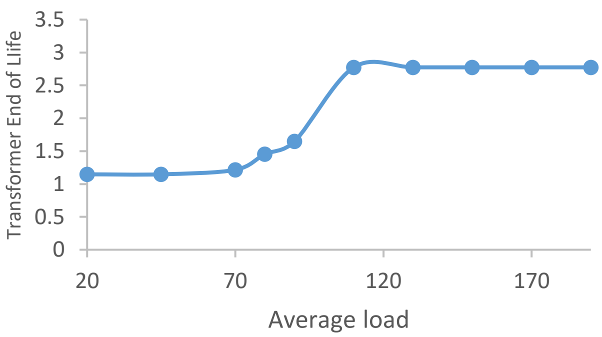


Fig 6. Effect of average load on $TxEoL_{Y0}$.

Transformer lifespan is longest for average load below 70% as shown in Figure 6.

G. Impacts on aging

Transformers age after manufacturing. There are many contributing factors to transformer aging. For oil filled transformers, the windings and insulations are submersed in oil and chemical reactions take place. Insulation loses its mechanical strength as well as its insulation strength. Degree of Polymerization (DP) of insulation is a measurement of aging of insulation in transformer. When it falls below 200, the transformer insulation is considered to be deteriorated and the transformer will be refurbished or replaced [22].

There is a high correlation between age and $TxEoL_{Y0}$. Transformer aging is generally measured following DGA analysis described in Section III(B). Transformers deteriorate faster between 30 to 45 years of age as shown in Figure 7.

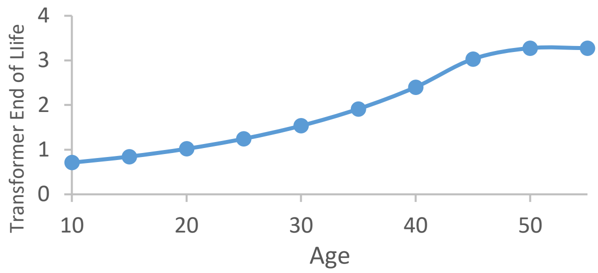


Fig 7. Effect of age on $TxEoL_{Y0}$.

H. Impacts of humidity

There is a positive co-relation between relative humidity and $TxEoL_{Y0}$ as shown in Figure 8. Insulation tends to deteriorate faster with higher water content in oil.

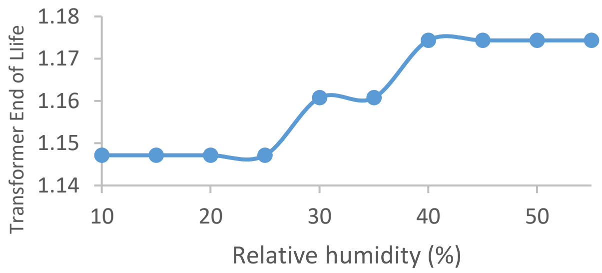


Fig 8. Effect of relative humidity on $TxEoL_{Y0}$.

I. Oil breakdown voltage effects

There is a negative correlation between breakdown voltage and $TxEoL_{Y0}$. There can be a 2.6% increase in $TxEoL_{Y0}$ depending on oil breakdown voltage as shown in Figure 9. It should be above 35 kV for sustainable operation of transformer.

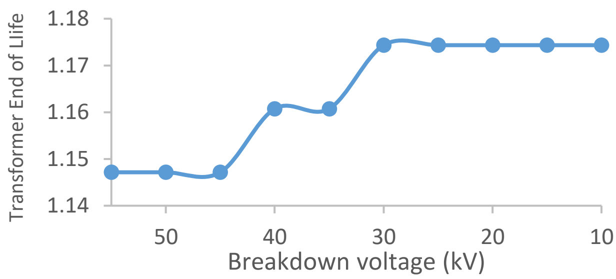


Fig 9. Effect of breakdown voltage on $TxEoL_{Y0}$.

J. Oil acidity

There is a positive co-relation between acidity and $TxEoL_{Y0}$. Acidity levels in oil plays a much more significant role in transformer's health as seen Figure 10. It should be below 0.25 (mg KOH/g).

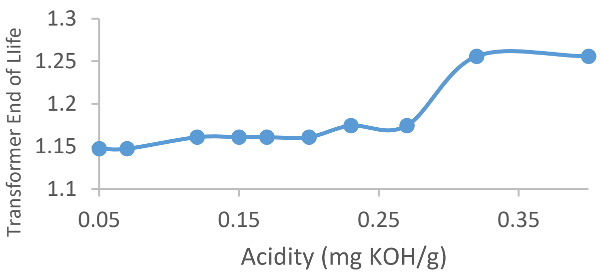


Fig 10. Effect of acidity on $TxEoL_{Y0}$.

K. Main tank surface condition

There is a positive correlation between surface deterioration and $TxEoL_{Y0}$. Figure 11 shows that the main tank surface condition rating exponentially affects the transformer's end of life after rating 3.

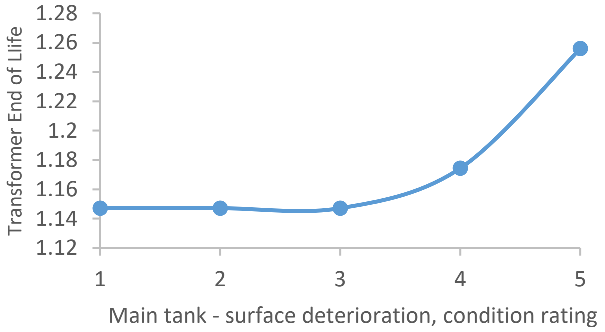


Fig 11. $TxEoL_{Y0}$ for different values of main tank - surface deterioration, condition rating.

L. Oil leaks condition rating

There is a positive co-relation between surface deterioration and $TxEoL_{Y0}$. In Figure 12, the impact of oil leaks can be seen. There is a significant deterioration in a transformer's health due to main tank oil leaks between condition rating 2 and 3. Here 1 is very good condition and 5 is the worst condition.

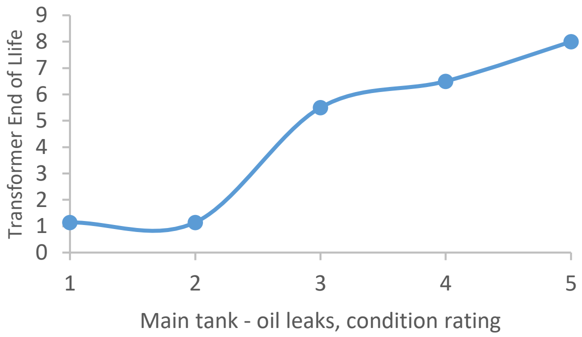


Fig 12. $TxEoL_{Y0}$ for different values of main tank - oil leaks, condition rating.

M. Radiator fins

There is a positive correlation between radiator fins surface deterioration and $TxEoL_{Y0}$. In Figure 13, radiator fins have less significant impact than other components of a transformer. Oil leaks in radiator fins impacts in a similar way as shown in Figure 14.

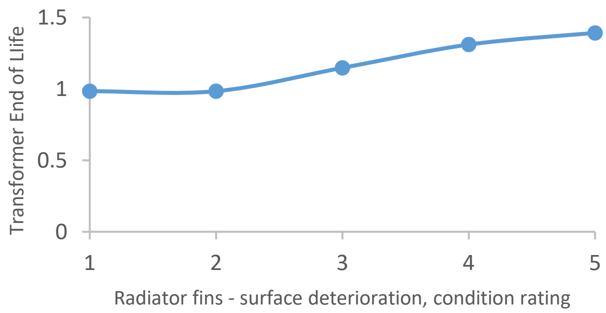


Figure 13. $TxEoL_{Y0}$ for different values of radiator fins - surface deterioration, condition rating.

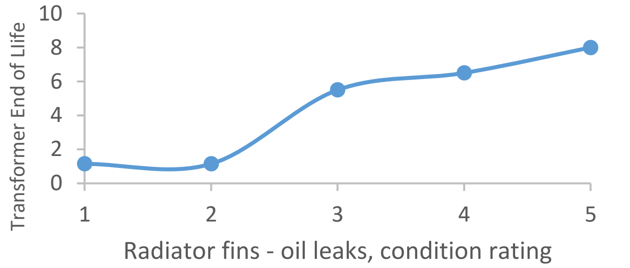


Fig 14. $TxEoL_{Y0}$ for different values of radiator fins - oil leaks, condition rating.

N. Conservator

There is a positive correlation between conservator surface deterioration and $TxEoL_{Y0}$. Surface deterioration of conservator impacts significantly after condition rating 4 as shown in Figure 15. Oil leaks in the conservator tank also has positive correlation with $TxEoL_{Y0}$ as shown in Figure 16.

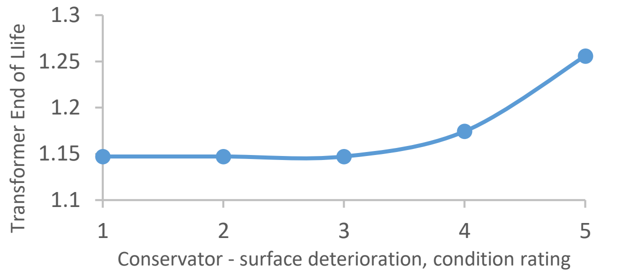


Fig 15. $TxEoL_{Y0}$ for different values of conservator - surface deterioration, condition rating.

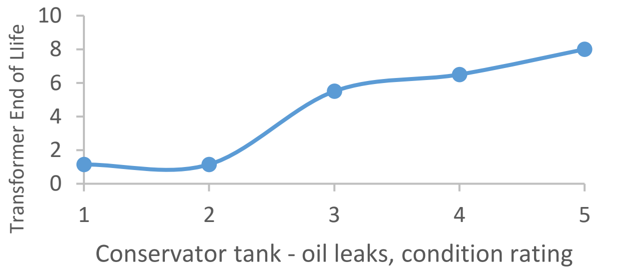


Fig 16. $TxEoL_{Y0}$ for different values of conservator tank - oil leaks, condition rating.

O. Cable end box

There is a positive correlation between cable end box - condition and $TxEoL_{Y0}$. Transformer end of life depends less on cable end box – condition as shown in Figure 17.

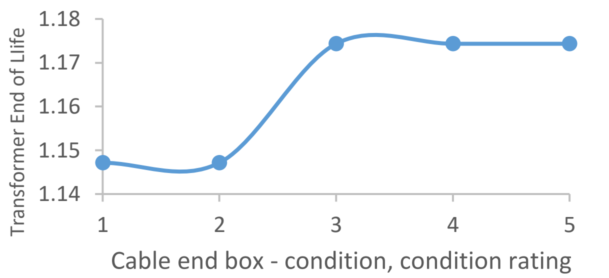


Fig 17. $TxEoL_{Y0}$ for different values of cable end box - condition, condition rating.

P. DGA and FFA

There is a linear relationship between end of life obtained from DGA and FFA with transformer end of life in this case as shown in Figure 18. If EoL results from these tests are higher than other variables, then the maximum of these is taken to the final end of life of the transformer.

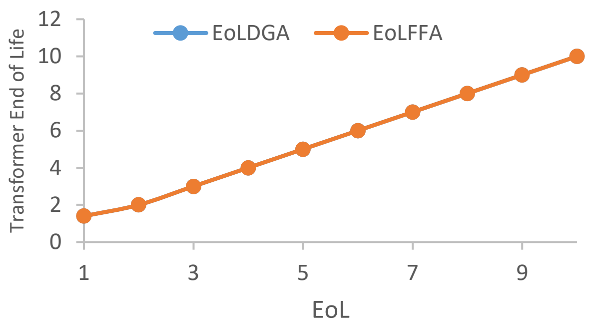


Fig 18. $TxEoL_{Y0}$ for different values of EoL_{DGA} and EoL_{FFA}.

IV. Recommendations

Transformers can be installed in an enclosed area for the installations in the industrial zones, so that the effect of pollution and dusts are less on the transformer asset. Moreover, it can protect the transformers from the direct sun light, so that transformers will not acquire additional heat during summer and its temperature will stay low. Furthermore, the EoL relationships indicate that the average loading of the transformer should be kept below 70% and maximum loading below 130%, thus helping to extend the service lifespan of the transformers significantly and it will be much more reliable than other highly loaded transformers.

The most critical factor remains the loading on the transformer and other lead assets and the extent to which a maximum and average demand loading characterizes the impact of widespread EV charging remains to be determined. The next stage of this research explores the expected demand on the grid and its impact on transformer temperature and associated EoL factors.

V. Summary

Transformer end of life ($TxEoL_{Y0}$) after several years (8 year in this case) of use are affected by many factors, such as distance to coast, altitude, corrosion zone, environment, demand, age, humidity, acidity, breakdown voltage etc. Some factors have a greater impact. Distance to coast significantly affects the $TxEoL_{Y0}$. Similarly, mass roll out of EV will also impact the aging of transformers by increasing the energy demand. Unlike distance to coast, quality of environment has a linear relationship with $TxEoL_{Y0}$. On the other hand, demand both maximum and average, have the most significant effect on $TxEoL_{Y0}$. Age has an exponential effect on $TxEoL_{Y0}$ after 45 years. Breakdown voltage has an inverse linear effect on $TxEoL_{Y0}$. Oil leak is the most significant among the other factors affecting $TxEoL_{Y0}$. Finally, DGA and FFA has a linear relationship with $TxEoL_{Y0}$.

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